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A METHOD TO MEASURE THE RATIO OF TOTAL TO SELECTIVE EXTINCTION TOWARD BAADE'S WINDOW

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ABSTRACT

We present a method to measure the ratio of total to selective extinction, $R_{VI} \equiv A_V/E(V-I)$, toward Baade's window by comparing the VIK colors of 146 Baade's window G and K giants from Tiede, Frogel, & Terndrup with the solar neighborhood $(V-I)$, $(V-K)$ relation from Bessell & Brett. We show that the statistical errors of this approach are $\sim$0.7%, an order of magnitude smaller than the only previous measurement of this quantity, and that the measurement has at most a weak dependence on stellar type from G0 to K4. However, the systematic error, which arises from uncertainties in the photometric zero points, is much larger: using the Tiede et al. zero points we obtain $R_{VI} = 2.28$, while the OGLE II zero points yield $R_{VI} = 2.40$, a difference of 5%. Hence, determination of the photometric zero points will be critical to obtaining an unambiguous measurement of R_{VI}.

Subject headings: distance scale — dust, extinction — Galaxy: center

1. INTRODUCTION

The ratio of total to selective extinction, $R_{VI} \equiv A_V/E(V-I)$, toward Baade's window is an important quantity for studies of both the distance scale and stellar populations. For example, the optical extinction toward Baade's window is most directly determined in V (Stanek 1996; Gould, Popowski, & Terndrup 1998; Alcock et al. 1998), but the absolute magnitude of clump giants is most robustly known in I (Paczyński & Stanek 1998). Knowledge of R_{VI} is therefore required to measure the Galactocentric distance from clump giants. As another example, an important indication that M giants in Baade's window are intrinsically different from those in the solar neighborhood is that they have different colors at fixed spectral type (Frogel & Whitford 1982, 1987; Tiede, Frogel, & Terndrup 1995). To determine the intrinsic colors of stars in Baade's window, one must know the ratio of total to selective extinction in those colors. Intensifying interest in these questions over the past several years has focused increasing attention on R_{VI}.

Paczyński & Stanek (1998) found that the $(V-I)$ colors of clump giants in Baade's window were anomalous in the sense that, after correction for extinction, they were redder in $(V-I)_0$ than clump giants in the solar neighborhood by 0.2 mag. Stutz, Popowski, & Gould (1999) found a similar offset (0.17 mag) for RR Lyrae stars in Baade's window compared to those in the solar neighborhood at the same $(V-K)_0$. Popowski (2000) showed that part of these offsets was simply due to errors in the original photometry used by both groups. When he incorporated the revised OGLE photometry of Paczyński et al. (1999), he found that the offset in $(V-I)_0$ shrank to $\sim$0.11 mag in both cases.

Popowski (2000) then reviewed the various attempts to explain such an offset in terms of a difference between the intrinsic properties of stars in the two populations, an idea advanced by Paczyński (1998) and by Stutz et al. (1999). He argued that such an explanation was not impossible, but unlikely, and that a more plausible explanation is that the value $R_{VI} \equiv A_V/E(V-I) = 2.5$ adopted by both Paczyński & Stanek (1998) and Stutz et al. (1999) from Stanek (1996) was incorrect. Both color anomalies could be solved, he noted, by adopting $R_{VI} = 2.1$. Popowski (2000) used this reevaluation to draw various conclusions about the extragalactic distance scale.

From a conceptual standpoint, Stanek's (1996) determination, which is based on the method of Woźniak & Stanek (1996), is extremely straightforward. In essence, he simply measures the regression of the mean color of the red clump on its mean magnitude. That is, if there is more dust along one line of sight than another, then the clump should be both fainter and redder, and the ratio of these changes is just the ratio of total to selective extinction, R_{VI}. The major difficulty in applying this method in practice is that one must make some assumption about R_{VI} in order to identify the "clump" in the first place, i.e., in order to distinguish it from the "background" of first-ascent giants. Woźniak & Stanek (1996) were acutely aware of this difficulty and conducted extensive tests to determine how initial assumptions about R_{VI} would affect the final results. After reviewing these tests, K. Stanek (2000, private communication) judges the errors in the Stanek (1996) determination to be

$$R_{VI} \equiv \frac{A_V}{E(V-I)} = 2.5^{+0.1}_{-0.15} \quad \text{(Stanek 1996)} . \qquad (1)$$

To the best of our knowledge, this is the only previous measurement of R_{VI} toward Baade's window. The value adopted by Ng et al. (1996), $R_{VI} = 2.4$, appears to have been taken from Woźniak & Stanek (1996). After considerable effort, we are unable to trace the origin of the $R_{VI} = 2.25$ adopted by Tiede et al. (1995). Table 1 gives a summary of values of R_{VI} reported in the recent literature.

Here we present a new method to determine R_{VI} based on a comparison of the observed VIK colors of G0–K4 giants with their intrinsic colors, which are *assumed* to be the same as those of similar stars in the solar neighborhood (Bessell & Brett 1988). For the Baade's window stars, we use a sample of 146 stars from Tiede et al. (1995). We find that if we use the original Tiede et al. (1995) photometry, we obtain

$$R_{VI} = 2.283 \pm 0.016 \quad \text{(Tiede zero points)} , \qquad (2)$$

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TABLE 1

R_{VI} VALUES IN THE RECENT LITERATURE

Source	R_{VI}	Remarks
This paper	2.283 ± 0.016	Tiede et al. 1995 photometry
This paper	2.403 ± 0.018	OGLE II photometry
Stanek 1996...........	$2.5^{+0.1}_{-0.15}$	Method: Woźniak & Stanek 1996
Ng et al. 1996	2.4	Adopted from Woźniak & Stanek 1996?
Tiede et al. 1995......	2.25	Method unknown

while if we adjust the optical (VI) zero points according to the OGLE II calibration (Paczyński et al. 1999), we get

$$R_{VI} = 2.403 \pm 0.018 \quad \text{(OGLE II zero points)} . \tag{3}$$

As we discuss in § 3, it is by no means clear which, if either, of these zero-point determinations is correct. Hence, at present the systematic error in R_{VI} toward Baade's window is almost an order of magnitude larger than the statistical error.

2. MEASUREMENT OF R_{VI}

To measure R_{VI}, we assume that the VIK colors of giant stars in Baade's window are the same as those in the solar neighborhood as determined by Bessell & Brett (1988). Bessell & Brett (1988) give VIK colors from G0 to M5, that is, over the color range $1.75 \le (V-K)_0 \le 5.96$. However, there is considerable evidence that the spectral energy distributions of M giants (at fixed spectral type) differ significantly between Baade's window and the solar neighborhood (Frogel & Whitford 1982, 1987; Tiede et al. 1995). This does not necessarily mean that the $(V-I)$, $(V-K)$ color-color relation is different, and in fact we will present evidence below that it is not. However, to be conservative, we restrict consideration to $(V-K)_0 \le 3.5$, which eliminates all M giants and K5 giants as well. That is, we consider only stars with

$$1.75 \le (V-K)_0 \le 3.50 . \tag{4}$$

We begin with the sample of 509 stars with optical and infrared photometry from the BW4b field of Tiede et al. (1995). Note that the columns headed V_0 and $(V-I)_0$ in that paper actually give V and $(V-I)$. We recover the original K magnitudes using the equation $K = K_{0,\mathrm{Tiede}} + 0.14$, as indicated by Table 1 of Tiede et al. (1995). We then obtain $(V-K)_0$ using visual extinctions, A_V, from Stanek's (1996) extinction map together with the relation,

$$A_K = 0.11 A_V . \tag{5}$$

Note that the Stanek (1996) map[3] has been corrected to the zero point found by Gould et al. (1998) and Alcock et al. (1998). These authors made their zero-point determinations by comparing the $(V-K)$ colors of local K giants and RR Lyrae stars, respectively, with the $(V-K)$ colors of similar stars in Baade's window, making use of the extinction ratio given by equation (5). Hence, for consistency, we use the same ratio here.

Unfortunately, there are surprisingly wide discrepancies in the zero points of optical photometry toward Baade's window, which turn out to vary not only by author but by field position. D. Terndrup (2000, private communication) together with collaborators is evaluating and studying these discrepancies, and he has generously made available in advance of publication the offsets between the OGLE II system (Paczyński et al. 1999) and the Tiede et al. (1995) system *for the specific field locations used in the present study*. He finds that the zero points differ by $V_{\mathrm{OGLE}} - V_{\mathrm{Tiede}} = 0.098 \pm 0.005$ and $(V-I)_{\mathrm{OGLE}} - (V-I)_{\mathrm{Tiede}} = 0.005 \pm 0.005$, and that there is little trend or scatter in these offsets other than that accounted for by measurement errors. For purposes of presenting our method, we adopt the OGLE II system, which is the more recent and has been the subject of a systematic investigation by Paczyński et al. (1999). We therefore adopt colors adjusted by

$$(V-I)_{\mathrm{adopted}} = (V-I)_{\mathrm{Tiede}} + 0.005 ,$$
$$(V-K)_{\mathrm{adopted}} = (V-K)_{\mathrm{Tiede}} + 0.098 . \tag{6}$$

However, as we discuss in § 3, the problem of optical zero points in Baade's window is by no means resolved. Thus, we will compare the results obtained using equation (6) with those found using the original Tiede et al. (1995) photometry.

Of the original 509 Tiede et al. (1995) stars, 185 lack VI photometry. Of the remainder, 86 lack A_V measurements because they fall within 2′ of NGC 6522, where Stanek (1996) found the A_V determinations to be unreliable. A further 87 stars are bluer than the color interval in equation (4), and an additional five stars are redder. This leaves a total of 146 stars.

For each of these 146 stars, we use linear interpolation to estimate the $(V-I)_{0,\mathrm{Bessell}}$ predicted from their measured $(V-K)_0$ and the Bessell & Brett (1988) VIK color-color relation. We then fit the data to a two-parameter model

$$(V-I) - (V-I)_{0,\mathrm{Bessell}} = \alpha A_V + \beta[(V-K)_0 - 2.405] , \tag{7}$$

where the offset 2.405 is chosen to eliminate the correlation between α and β.

We remove outliers as follows. We do the fit using all the data, and determine the "errors" by forcing χ^2 per degree of freedom to unity. We find the largest σ outlier, eliminate it, and repeat the process. We stop when the largest outlier is less than 3 σ. This eliminates seven outliers. We find

$$\alpha = 0.4161 \pm 0.0032 , \quad \beta = -0.0236 \pm 0.0132$$
$$[1.75 \le (V-K)_0 \le 3.50] . \tag{8}$$

Since $R_{VI} = \alpha^{-1}$, we obtain equation (3). From the fact that β is consistent with zero at the 1.8 σ level, we conclude that the shift from $(V-I)$ to $(V-I)_0$ depends mainly on A_V and depends at most weakly on the color of the star. We therefore set $\beta = 0$ and show our resulting fit in Figure 1. Note that since R_{VI} will in general be a function of color or spectral type, our measurement should be taken as applying to stars at the mean of our sample, $(V-K)_0 = 2.40$, i.e.,

[3] Available by anonymous ftp at ftp://astro.princeton.edu/stanek/Extinction.

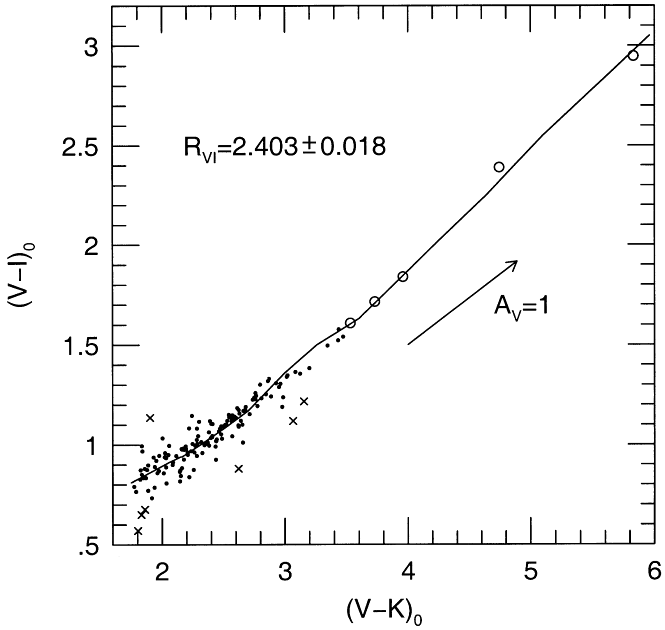

FIG. 1.—Color-color $(V-K)_0$ vs. $(V-I)_0$ plot of 151 Baade's window giant stars (*points*) together with the color-color relation (*solid curve*) of solar neighborhood stars taken from Bessell & Brett (1988). The $(V-I)_0$ color is determined from VK photometry of Tiede et al. (1995) adjusted to the OGLE II zero point (Paczyński et al. 1999) and corrected for extinction according to Stanek (1996), assuming $E(V-K) = 0.89A_V$. The $(V-I)_0$ color is determined in this paper by fitting for $R_{VI} = A_V/E(V-I)$, essentially by moving the points vertically until they straddle the curve. Five red stars (*open circles*) were excluded from the fit because of concerns that the spectral energy distributions of Baade's window M giants are different from those of M giants in the solar neighborhood. Seven outliers (*crosses*) were also excluded from the fit. The arrow shows the effect of 1 mag of V-band extinction. Since this arrow is parallel to the color-color curve, even large errors in the extinction cannot affect the results.

K0–K1 giants. The value $R_{VI} = 2.40 \pm 0.02$ agrees within errors with the only previous determination (Stanek 1996), $R_{VI} = 2.5^{+0.1}_{-0.15}$.

Also plotted on Figure 1 are the five stars (*open circles*) that were excluded from the fit because they were too red. Note that they lie very close to the local VIK curve of Bessell & Brett (1988). If we repeat the entire procedure including these five stars, we obtain

$$\alpha = 0.4168 \pm 0.0032 \ , \quad \beta = -0.0116 \pm 0.0088$$
$$[1.75 \leq (V-K)_0 \leq 5.96] \tag{9}$$

with seven outliers excluded. That is $R_{VI} = 2.399 \pm 0.018$, essentially identical to equation (3). In this case, the slope β is even more consistent with zero, indicating that our determination is not a significant function of spectral type.

This weak dependence on $(V-K)_0$ color appears to be in strong conflict with Figure 14 of Tiede et al. (1995), which shows a large number of points in the range $4 < (V-K)_0 < 6$ that lie $\sim$0.3 mag below the Bessell & Brett (1988) relation. In fact, all the points with CCD VI photometry from Tiede et al. (1995) lie close to the line (as they do in our Fig. 1). The remaining points are from Frogel, Whitford, & Rich (1984) and Frogel & Whitford (1987), who obtained their own single-channel infrared data but relied on the earlier photographic data of Whitford & Blanco (1979) and Arp (1965) for the VI photometry. From the small overlap between these older photographic data and the CCD photometry reported in Tiede et al. (1995), we estimate that the earlier photographic photometry may have a zero-point error of $\sim$0.3 mag in $(V-I)$ in the sense of being too blue. If this zero-point error is confirmed by future observations, it would mean that the $(V-I)$, $(V-K)$ color-color relation is the same for Baade's window and the solar neighborhood, but this would not necessarily imply the same correspondence between colors and spectral type in the two locations. Nevertheless, to be conservative, we have based our results only on the G0–K4 sample.

3. DISCUSSION

The accuracy of the determination of R_{VI} presented here depends critically on the zero points of the underlying photometry. Tiede et al. (1995, Table 2) believe that their K-band calibration is accurate to better than 0.016 mag. An error of this amplitude would change R_{VI} by only about 1%, roughly the statistical error in equation (3). However, it should be noted that there are no independent checks of this calibration.

Of more direct concern are the differences in the determinations of the optical (VI) zero points as found by various authors. These differences are under investigation by D. Terndrup (2000, private communication) and his collaborators and will not be discussed in detail here. However, as we mentioned in the Introduction, had we simply adopted the Tiede et al. (1995) optical photometry, which is ultimately derived from Terndrup (1988) and Terndrup & Walker (1994), without the adjustments given by equation (6), then we would have obtained $R_{VI} = 2.28$. This would go a long way toward solving the "anomalous color" problem of bulge RR Lyrae stars (Stutz et al. 1999), reducing it to 0.05 mag. By contrast, our result using the OGLE II–based adjustment leaves the problem at 0.09 mag, almost twice as large.

One might be inclined to simply adopt the more modern OGLE II photometry. One argument for doing so is that D. Terndrup (2000, private communication) finds that the offsets between OGLE II and Tiede et al. (1995) differ from place to place corresponding to the regions imaged by the smaller CCDs that were available to Terndrup (1988) and Terndrup & Walker (1994). Unfortunately, the situation is hardly so clear cut. For example, Stanek et al. (2000) analyzed their own photometry of the OGLE BW8 field, and found a clump color anomaly of only 0.056 mag, about half the size of the OGLE II value of 0.11 mag as recalculated by Popowski (2000). Since the clump anomaly (in contrast to the RR Lyrae anomaly) is affected only by the $(V-I)$ zero point, this implies the Stanek et al. (2000) and OGLE II systems must differ by approximately

$$(V-I)_{\rm Stanek} \simeq (V-I)_{\rm OGLE\ II} - 0.054 \ . \tag{10}$$

Thus, while the OGLE II $(V-I)$ zero point is in nearly perfect agreement with Tiede et al. (1995), it strongly disagrees with Stanek et al. (2000). If we were to adopt a color correction $\Delta(V-I) = -0.054$, it would alter our estimate of R_{VI} by approximately $\Delta \ln R_{VI} = -\Delta(V-I)R_{VI}/\langle A_V \rangle \sim$ 9% to $R_{VI} \sim 2.6$. Here $\langle A_V \rangle \simeq 1.48$ is the mean extinction of the giants in our sample. At present, then, it seems prudent to wait until this zero-point controversy is resolved before making a definitive statement about R_{VI}.

Since there will inevitably be zero-point errors in the photometry at some level, it is important to quantify exactly how any such errors will affect the final result. If we write the difference between the measured and true colors as $(V-I)_{\rm meas} - (V-I)_{\rm true} = \delta(V-I)$, and similarly write $V_{\rm meas} - V_{\rm true} = \delta V$ and $K_{\rm meas} - K_{\rm true} = \delta K$, then it is straightforward to show that the inferred R_{VI} deviates from the true one by approximately

$$\frac{R_{VI,\,\rm inferred}}{R_{VI,\,\rm true}} \simeq 1 + \frac{R_{VI}}{\langle A_V \rangle}\left[S(\delta V - \delta K) - \delta(V-I)\right] , \quad (11)$$

where $\langle A_V \rangle = 1.48$ is the mean extinction of the sample and $S \simeq 0.43$ is the slope of the color-color relation shown in Figure 1. For the differences given in equation (6) between the Tiede et al. (1995) and the OGLE II photometry, equation (11) predicts a 5.6% difference in the inferred values of R_{VI}, in good agreement with the $\sim$5% difference found by direct numerical evaluation. Hence, if the zero-point errors were reduced to 0.01 mag, then R_{VI} could be determined to $\sim$2%.

Finally, we note an important implication of the zero-point discrepancy that we have identified. The zero point of the Stanek (1996) extinction map is currently set by $\langle A_V \rangle$ measurements using K giants (Gould et al. 1998) and RR Lyrae stars (Alcock et al. 1998). These studies each found the same zero point, and each with an error of about 0.05 mag. Hence, they could be safely combined. However, Gould et al. (1998) used V-band photometry from Tiede et al. (1995), whereas Alcock et al. (1998) used MACHO V photometry which they confirmed to be the same as OGLE I photometry to within 0.02 mag. Paczyński et al. (1999) found that OGLE II was brighter than OGLE I by 0.02 mag. Hence, the system used by Alcock et al. (1998) was quite similar to the OGLE II system. Thus, if OGLE II photometry is adopted as the standard, then the Alcock et al. (1998) result remains approximately the same, whereas the Gould et al. (1998) determination of $\langle A_V \rangle$ should be moved higher by 0.11 mag. The two results are then mildly discrepant at the 1.5 σ level. If they were nevertheless combined, the extinction zero point would be moved higher from its present (Stanek 1996) value by 0.05 mag. However, at the present time we do not consider the zero-point problem to be settled enough to warrant making this small adjustment.

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